AUTOMATED COMPOSITE DRAPING: A REVIEW

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ABSTRACT

The automated forming of high quality composite components has been the subject of a large volume of research over the last 30 years. This paper provides a summary of the challenges involved in composite layup and reviews a wide range of novel processes that have been developed, with a focus on producing high quality components from sheet material. The key themes and common approaches are identified, alongside a selection of more novel approaches which seek to solve key issues. The conclusion is that while many of the basic aspects of automation have been successfully covered, there is a considerable amount of repeated work and some of the core challenges have yet to be successfully solved.

1. INTRODUCTION

As composite materials are increasingly used in commercial aerospace and automotive applications the existing manufacturing methods are struggling to match the required production volume demands [1]. In comparison to metallic materials, Advanced composite materials pose a variety of unique forming challenges. They generally consist of thousands of typically carbon fibres embedded in a polymer based matrix. The fibres themselves have excellent tensile properties, but without a matrix to hold them all together they are essentially useless as an engineering material. Fibres are therefore embedded in polymer based resins, either thermosetting or thermoplastic, forming a functional material.

2. WHY IS COMPOSITE FORMING DIFFICULT?

To fully utilise the performance of the fibre-matrix combination the fibres need to be as aligned and as well bonded to the matrix as possible. In reality this is not always achieved, and there are several common defects which can appear in laminates:

- Wrinkles: Fibres are no longer aligned reducing its structural properties [2].
- Dry Spots: Without matrix support, the fibres can just buckle and fail under compression
- Bridging and Resin rich areas: Bridging of fibres across and concave corner in the mould can cause resin rich areas which can fail in compression and can cause dry spots elsewhere in the laminate from where resin has been drawn in [3].

It is the process of forming fibres into shape while avoiding these defects that makes composite manufacturing such a difficult process. A review of all the current composite manufacturing methods could take up an entire volume of a journal, so this paper will focus only on processes that involve continuous fibre sheet materials and wider perspective on composite manufacture is given in a recent review paper from Nottingham University [4]. As a raw material, the majority of composite materials come in sheets or tapes made up thousands of Fibres, either uni-directional, woven or biaxial. Very few actual production parts consist of just flat or singly curved shapes and they frequently contain integrated out-of-plane features such as stiffeners, sandwich panels or brackets which can significantly increase the complexity of the layup process [5]. In the context of layup, ‘complexity’ can means many things. Some publications consider ‘complex’ to be the introduction of even very mild double curvature [6], [5]. In a wider context complexity can be defined by the frequency and severity of geometries such as single and double curvatures, tight internal radii or internal recesses.

The real difficulty in making effective composite structures is turning these sheets of fibrous material into 3D shapes, a process often referred to as 'draping' [4]. It is worth discussing this process in detail before reviewing any specific manufacturing processes. For flat, single curvature or more specifically 'developable surfaces', this can be achieved *without* any in-plane deformation. However, most components feature some double curvature which is by definition 'un-developable' meaning in-plane deformation *will* be required [7]. The fibres themselves cannot stretch along their length, but they can bend in-plane which when combined with the woven structure allows the ply structure to 'shear' in-plane as a whole. This shear deformation enables the forming of otherwise undevelopable shapes [8]. The location and direction of this shear deformation within the ply depends on the geometry, the orientation of the fibres *and* the order of layup, as depicted in Figure 3. The middle of the three images schematically shows a ply with a nominal 0˚/90˚ orientation with the shear deformation located in the four corners of the picture. The right hand image shows the same shape but with the ply at a +/- 45˚ orientation and the shear forms in different locations. It is the localised and anisotropic nature of this shear deformation, added to the flexible, sometimes 'sticky' and non-linear behaviour of composite material that makes composite forming such a difficult process to automate [9].

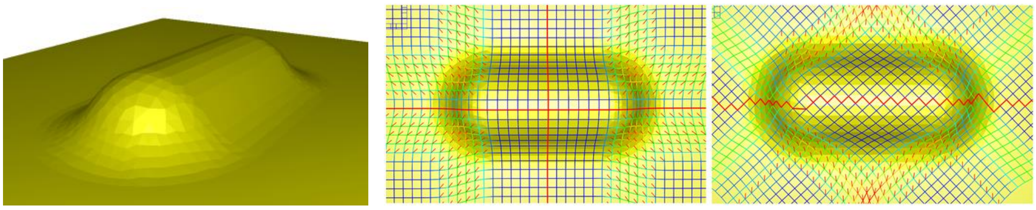

Figure 1: Schematic of how plies can shear over the mould shape generated using 'Virtual Fabric Placement [8].(Left) Image of the formed shape (Middle) 0˚/90˚ orientation, (Right) +/- 45˚ orientation.

3. NOVEL AUTOMATED PROCESSES

One of the difficulties of investigating and comparing prototype manufacturing processes is that much of the work is industrially linked hence much of it may be unpublished, and even when it is, there is generally a lack of quantitative or in some cases even qualitative information about the processes capabilities. Often publications will give only a single component as an example and will not specify the time taken, the reliability or any other problems. Thus to an extent the capabilities have to be inferred from the available information, making direct comparisons very difficult. Additionally it must always be remembered that these new sheet forming processes must be compared not just to each other but to all available process including those that use tapes, patches or discontinuous fibres. For example if it proves that it is impossible to automated the production of the most complex shapes without introducing significant wrinkling, it may be that discontinuous fibre solutions will be future [10]. It must also be considered that although many current processes all have their own limitations, they carry a considerable inertia in industry in terms of financial investment, knowledge and certification [11]. Thus any new process would need to bring a *significant* advantage over these existing processes in order to break into the market.

3.1. The elements of layup:

Layup of sheet material can be broken down into three 'elements'; 'Pick and place', 'Shaping' and 'consolidation'. In some processes combinations of these occur at the same time, hence they are referred to as ‘elements’ rather than ‘stages’ of ‘phases’. The term ‘draping’ is often used in literature, and generally refers to a combination of the three elements identified here.

An alternative to working with whole plies is to build up layers from thin tapes, as used in Automated Tape laying (ATL) and Automated Fibre Placement (AFP). A thorough review of both these processes is already available [11]. The review concluded that ATL is very capable of making flat, high quality laminates but struggles when curvature is introduced. AFP is capable of simple double curvature shapes because it uses thinner tapes to allow greater in-plane curvature. However they can suffer from wrinkling, ply fold-over and gaps when curving around double curvature complex shapes [12][13]. The initial start-up costs of both these processes are very high but for the right application such as wing spars and skins they can be successful. Filament winding, pultrusion and braiding are also not included in this review as they are fundamentally limited to cylindrical type shapes.

3.2. Element 1: Pick and place

3.2.1. Rigid Flat to flat

Individual plies are generally cut out from a stock of material that has been rolled over a large table. The role of ‘pick and place’ robots is generally to rapidly re-arrange the cut plies into kits for each component [14]. One of the most commonly used solutions for picking and placing of flexible thin plies is to essentially ‘make them rigid’ by securing them with grippers mounted on a rigid frame, as shown in Figure 2. The plies can be gripped using a range of different grippers such as vacuum, needle, electrostatic or others. There are several in-depth studies of gripper types and their relative merits, with each concluding that there is no ‘do-it-all’ gripper solution [18][19][20]. The choice of gripper will vary based on factors such as the permeability, thickness and mass per unit area of the material. Other factors such as strict requirements for contortion free contact and no contamination can also effect this choice. Most solutions consist of multiple separate grippers attached to a rigid frame which is manoeuvred by a robot. Early examples such as Chestney in 1996 [21] have been followed up by many similar systems all capable of moving individual plies from one flat location to another [22][23]. One of the most advanced and flexible systems is presented by Reinhart, where over 4000 individual vacuum ports can be individually controlled to pick up different ply shapes. Systems that are more integrated into a production environment which can move plies from a cutting table to a mould or ply stack are proposed by NRL [25] and Technalia [26] who integrate visual inspection quality control and LOOP technologies [27], who advertise an integrated Software system to enable fully automated picking from a cutting table. However the rigid frames used by this systems restrict these systems from moving plies to and from curved or contoured surfaces. Some systems use a rigid but already contoured frame which is specific to the geometry of particular parts. Examples include a system used to move carbon car bonnets between a press and mould [28], or a needle gripper equipped solution presented by Schmalz for handling RTM preforms [29].

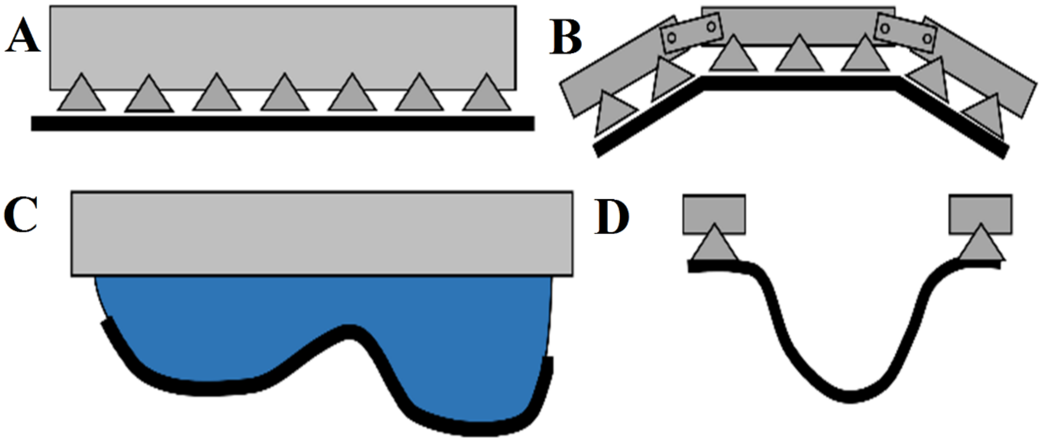

Figure 2: Example schematics of the four common ply handling methods: (A) Rigid, (B) Kinematic, (C) Compliant and (D) Free Ply.

3.3. Element 2: Shaping

3.3.1. Combining Picking, placing and forming.

For any component that isn't just a flat sheet, an automated system will not only need to pick up the ply but it will need to deform it to the shape of the mould. Achieving this without generating any wrinkles or other defects is one of the most difficult aspects of layup. In RTM moulding in particular shaping or 'preforming' of the dry fibres is one of the major cost drivers [30]. Methods for making high quality components tend to favour a layer-by-layer approach, allowing each layer to be individually laid and inspected to eliminate defects. Full stack forming of all the plies is desirable as it can potentially enable greatly reduced overall draping times [31].

A common technique used to enable ply placement over more complex contoured shapes is to mount the grippers onto a structure which can deform or articulate kinematically to match the shape of the mould as shown in image B of Figure 2. One of simplest examples is developed by 'FILL', where the grippers are mounted on linear actuators to allow a flat ply to be picked up and then shaped into a single curvature mould [32]. A different approach to achieving this is the 'Flex-ply' developed at the National Composites Centre, which used a large number of individual vacuum grippers attached to a flexible polymer sheet to pick up the plies [33]. Four robotic arms attached to the corners of the sheet are used to deform the sheet and ply together into the required shape and then place the ply on the mould. However the polymer sheet's in-plane rigidity may restrict its use for tight radii or double curvature shapes. An alternative approach is a system developed by Technische Universitat Braunshweig where electrostatic grippers are attached to an arm formed of multiple articulated linkages, allowing it to bend around a single curvature mould shape [34]. A similar principle is used by Gergross where the linkages can be deformed in multiple axis allowing double curvature layup [35].

Other concepts have used increasingly complex kinematic systems to allow conformity to increasing complex mould shapes. One example is the 'modular surface gripper' presented by Gerngross which features a grid of independently moveable grippers [35]. This is one of the few systems that directly cites the requirement and ability to create double curvature and the associated in-plane deformation described earlier in section 2. However this design is still limited to simple shapes. Loop technologies have developed the 'FibreFORM' systems which claims to be capable of fitting plies to 'fifth order polynomial' doubly curved shapes, such as 'fuselage sections, wing skins or engine nacelles', using an array of modular grippers [36]. A more specialised example is presented by Gerngross, where a bespoke mechanism was used to pick up flat plies, collapse them into a folded shape, and then partially expand, placing bagging materials into a double curved concave radar dish, in a similar manner to an unfolding umbrella [35]. A different take on kinematic forming was taken by Zhu, Siqi, where wide 280mm strips of glass fibre are sheared in 200mm sections by a kinematic linkage, allowing a basic steering of the tape along large curved components with a minimum radius of approximately 2m [37].

One downside of kinematic systems is that the complexity of the shapes they can conform to is rigidly dictated by the kinematics of the structure itself, with most systems only able to handle one or two features on the tool surface even if they are single curvature. A potential limiting factor to further development is that the number of linkages and actuators required to create larger and more complex components increases rapidly. To avoid this, there have been efforts to use passive compliant elements which are deformed by the mould itself as the whole system is lowered onto the surface as shown in image D of Figure 2. Another concept presented by Gerngross uses a simple kinematic linkage to approximately deform to the tool shape while a foam layer allows the ply to fully conform to the tool surface [35]. The open cell foam also acts as a gripper, as fans draw air through the foam to create enough air flow to lift and secure the ply. In another such example Angerer uses a large highly deformable roller with individual vacuum gripper cells around its perimeter to secure the ply [38][39]. The unique feature of this system is that the end effector 'rolls' across the part, deforming and laying down the ply as it goes, allowing the initial contact point and layup order to be tightly controlled. It has been shown to successfully drape dry cloth over very doubly curved shapes with some limitations to the forming depth. Another novel approach to the use of compliance consists of an air permeable bag partially filled with rigid granular beads [40]. Under normal conditions the granular material and bag can freely form into very complex shapes. However once a vacuum is applied the bag places the granular material under compression, causing it to 'jam', thus allowing the end effector to hold its deformed shape, be it flat or complex double curvature. The vacuum simultaneously secures the ply to the surface of the bag, enabling plies to be picked up and moved while remaining in shape.

A different approach to forming is the 'Continuous preforming for composite profiles' (COPRO), which is a continuous process similar to pultrusion where curved C sections are generated using a series of different shaped rollers to gradually form the tight curvatures and overall component shape [41]. This is however limited to continuous sections and only very mild double curvature. A variation of tape laying which is also worth reviewing as it can produce highly sheared tows is the 'Continuous Tow Shearing' (CTS) which can shear tapes of fibres to radii of curvature as low as 30mm while avoiding any wrinkling, overlaps and gaps. If such a system was attached to an articulated robot there may be potential to layup complex shapes. However the layup rate of the prototype is currently very low, at 3mm/s with narrow tapes [42].

3.3.2. Pick and place – Free ply forming

Many other projects have tried a different approach, where rather than securing the plies across their entire area and strictly dictating the formed shape, the ply is only held in a small number of discrete locations, generally around the perimeter and then left to 'hang' between them as shown in Figure 2. This is how plies are generally handled during hand layup, where a laminator will typically pick up the ply with each of their hands at opposing edges [43]. The out-of-plane bending stiffness of composite plies is relatively small, so plies will tend to 'sag' or form a type of catenary curve when clamped at its edges. Several studies have used this effect as a positive feature both to enable plies to be placed into deep convex moulds and also to dictate the location of the first contact between the ply and the mould [44][45].

One of the earliest systems was Buckingham and Newell in 1994 who used four robot arms to hold the corners of rectangular plies and transfer them to a variety of mould shapes [46]. They also developed a numerical model to predict the required gripper movement to achieve a specified arc shape [44]. A similar principle has been used multiple times since then. Molfino proposed a system which used four multi linkage robots to shape plies over double curvature but no details on performance have been published yet [47].

Stuttgart University are developing a system called 'Lowflip' to lay down wide tapes of Unidirectional ('UD') material up to 300mm wide where a pair of grippers attached to independent robots pick up the ply at either end and move it to the mould [48][49]. Once the ply is over the mould, a third robot with a roller end effector consolidates the ply while the two gripper robots adjust their position to regulate the tension in the ply and prevent unwanted contact with the mould. Another unique feature with this system is that each gripper is made up of independently mobile sections, allowing the UD ply to shear in-plane. This system is currently in development and its effectiveness is currently not know, but some wrinkling issues due to fibre misalignment in the stock material have been experienced [50]. A similar system is also being developed using two robots to grasp a strip or material and third to consolidate it onto a mould [51]. Currently this is only working on single curvature shapes but there are plans to move on double curvatures. Both these systems use materials and end effector are similar to those used in AFP and ATL systems, and it remains to be seen if it can overcome the issues of tow buckling, gaps and bridging experienced with many AFP based projects [12].

Another recent application of this style of process has been developed by the DLR in Germany [45], Two banks of articulated grippers attached to 6 axis robots were used to position large plies into a concave mould. Emphasis was placed on controlling the point of first contact and ensuring positional accuracy. They experienced some wrinkling of the ply during layup on the mould, attributed to the vacuum grippers slipping across the surface of the ply during transfer. This was eventually overcome by empirically adjusting the separation of the robots. The independent articulation of the banks of grippers has the potential to enable significant double curvature to be achieved.

3.3.3. Multi stage forming

All the above systems grasp the plies at the start of the layup process and then never let go until the ply is fully formed, relying on those initial grasping points to form the whole shape. In contrast during hand layup the ply is grasped, released and re-grasped multiple times. It was seen in the hand layup study by the author that the hands as well as grasping are often working together to achieve many different aims [43]. Examples included one hand securing of an area of the ply to the mould while the other hand either aligns the ply to a datum or applies tension to create shear. Other uses include using one hand for forming and sticking the ply to the mould while the other is used to support or rearrange the remaining 'unformed' region of the ply.

The major complication with this 'multi-stage' forming of plies is that once a small region of a ply is deformed in double curvature, it has a knock on effect on the curvature of the rest of the ply, causing it to fold, wrinkle or bend depending on the ply size and stiffness properties. Once this has happened identifying what to do next and locating specific points of the ply becomes much more challenging. In an early review paper on composite forming in 1990 [52], the key theme is sensor based robotic cells, which could theoretically give 'closed loop' control, deemed necessary by the inconsistent behaviour of prepreg materials. The key goals were "*Sensing, Intelligent decision making capability, Sophisticated handling techniques".*

Barring any mechanical malfunctions, robots will reproduce the same actions many times over to within a tight tolerance. Thus if the planned robot path is 'correct', the process will also be ‘correct’ every time. Working with humans, even the most experienced professional will do things slightly different every time, and will have to rely on their own closed loop control via visual and tactile feedback in order to achieve the desired result. The issue is that the inconsistent properties of composite material, especially prepreg can make the working environment particularly variable, such that there is unlikely to be single ‘correct’ robot path that could work perfectly every single time [53].

There are currently no systems for composites of which the author is aware that use genuine closed loop control. Many systems use vision based systems such as Laservision, manufactured by Assembly Guidance systems to check the ply placement after it has been laid down [54]. These are used only as a quality control check, and not as direct real time feedback control. In the metal pressing industry, machine vision has been used to create a ‘highly-flexible, low maintenance’ method for controlling placement of flat blanks into a press [55]. In composites forming industry humans currently have the monopoly on true mid-layup vision based control.

At the Automatica 2016 trade show there were a large number of off the shelf vision based robots systems such ‘Pick-it’, which could identify and pick up a wide variety of different shaped packaged food items, which geometrically have similar characteristics to a deformed ply [56]. However 26 years after the 1990 review, a new review by Sandhu still describes how robots vision systems have typically struggled with complex, curved and similarly coloured shapes which very accurately described a layup situation [57]. The development of ‘powerful processing tools’ is citied as the required next step to bringing vision into more complex environments like layup. The unpredictable nature of material behaviour during layup combined with the lack of closed loop feedback is likely the reason why all the robotic systems featured here pick up the ply from the flat table and then don’t release until the ply is fully formed in position.

There have been some previous examples of sequential grasping systems in an unstructured environment such as work carried out at the the University of California, Berkeley looking into folding of laundry [58][59]. Guided by complex vison based systems a two armed robot was able to sort a pile of laundry and neatly fold the articles in a pile. Impressive as this was, the robot operated much slower than a human. A more successful solution to this task is to use a human to navigate the randomly folded file of clothes, place them on a surface and then have an automated mechanism do the repetitive folding, a solution used industrially by products such as the Jensen Butterfly [60] or Foldi-mate [61].

While many of the schemes listed in section 3.3.2 try to use the ply handing system to shape the ply using a discrete number of end effectors, many other processes use stamping or membrane forming to achieve the finished shape in a single action, avoiding many of the issues of partial forming identified in section 3.3.3. However the specific complications of composite forming such as anisotropy and inability to plastically deform make press forming of composites a lot more difficult than with metallics.

3.3.4. Stamp forming

Stamping generally consists of a matching metal toolset, or one metal toolset combined with a large silicone pad. For simple shapes such as flat panels or for example snowboards, presses are highly effective and commercially available [62].The high cost of the required matched metal tooling is often prohibitive to the use of stamp forming technologies for small production runs or particularly large components. Concerns also centre on the potential for fibre wrinkling and breakage during forming [63]. Stamping is used successfully to preform stacks of woven plies for use in RTM by BMW who use matched tool sets with blank holders across the entire width of the ply to form body panels [64]. Unfortunately this process frequently produces wrinkles and other fibre deviations. To get round this, instead of being considered as 'defects' they were considered as 'manufacturing variations', a concept discussed in detail by Potter [3][65]. These variations can be accommodated into the structural design of the part and compensated for such that their presence no longer renders the part defective.

One of the common conclusions from academic studies on stamping is that using Blank holders to apply tension to the fibres during forming was shown to be highly beneficial to prevent wrinkling during this process [66]. Blank holders work by applying a through thickness pressure around the perimeter of the ply as the forming takes place. A study at Bristol University showed that complex shapes can be 'Presheared' into shape using a press equipped with blank holders, although the consolidation was done in a separate process [43].

3.3.5. Diaphragm forming

One approach to avoid the need for blank holders is 'Diaphragm forming', where plies are formed into shape by a vacuum while sandwiched between two deformable rubber diaphragms. The friction between the rubber diaphragm and composite ply takes the place of a blank holder by imparting tension into the prepreg. However, reservations remain about the cycle time and deformability of the diaphragms themselves, limiting its use for 'complex components'. Highly undevelopable shapes such as deep drawn hemispheres have been made using diaphragm forming, but crucially only with 0 ˚/90 ˚ laminates as far as the author is aware [67]. Adding +/- 45 ˚ layers has been shown to significantly change or inhibit the forming process increasing the in-plane compressive force dramatically [68]. For example, several studies used cross plied UD material to form parts with significant double curvature, but moving to quasi-isotropic layups both experienced serious wrinkling both in-plane and out-of-plane, directly citing the inter-ply friction as the cause of winkling [69], [70].

3.3.6. Hot drape forming

Hot drape forming is a variation of stamp forming that generally uses an ATL machine to build up a stack of plies, which is then mechanically formed over a male mould or die at an elevated temperature [71]. Hot drape forming machines are commercially available, but only for the production of single curvature parts [72]. A 'complex shape', which in truth was only mildly doubly curved compared to many examples, was attempted by Sorrentino but consistently produced wrinkles [5].

3.3.7. Other concepts

Pin bed forming, consisting of a large number of individually operated pins has been used to sequentially form woven carbon sheets into doubly curved shapes manipulate citing their flexibility as a key advantage [71]. In one particular application the pin bed was used to control the forming order, allowing the in-plane material deformation to be better controlled [73]. However, the complexity of the device, and the number of pins, increases with the *square* of both resolution and size, making scaling and complexity of components a major barrier to this approach.

The major aeroplane manufactures have a number of patents on novel forming processes [74]. For example Boeing Company presented a process where sheets of UD prepreg are tacked onto a custom rubber sheet which is then stretched, spreading out the tows and creating in-plane deformation. Alternatively Airbus present a novel solution to forming curved prepreg strips where sheets of UD prepreg pass through a series of cone shaped rollers [75]. The rollers produce a varied roller speed across their width, causing the prepreg to stretch on one side, creating a curve.

Two other systems are proposed by A+Plus systems for forming a joggled beam. One solution involves creating a preform with ATL that has out-of-plane 'waves' at the outer edges, which when locally straightened can provide extra material giving an effective in-plane deformation [76]. A second solution is to create preforms which feature an exaggerated bend that once straightened out to match a mould shape results in excess material at the edges which can allow greater double curvature.

3.4. Element 3: Consolidation

The final element of layup is to stick the ply down onto the mould or onto the previous ply. The ultimate aim is to reduce the amount of trapped air under the ply to the point where the cured laminate can be void free. In hand layup laminators use many different hand configuration alongside rigid tools to apply pressure to the ply [77]. This is often followed by a second consolidation process where the layup is placed into a vacuum bag, placing the whole layup under theoretically 1-bar of pressure. Vacuum consolidation has many positives, it does not require large forces to be applied, theoretically applies pressure to the whole ply at once and it requires very little equipment. However it has significant drawbacks. It is inherently limited to 1 bar pressure, which may be enough to consolidate flat plates, but higher pressure may be needed to form tight convex corners. Additionally in these corner areas a portion of the pressure applied by the outside air is reacted not by the mould surface but by in-plane tension in the vacuum bag and plies themselves [78]. Thus if there was a bridge in the ply prior to the vacuum being applied, these effects can reduce the actual through thickness pressure considerably, preventing the corner being correctly consolidated.

Another key issue with vacuum is the lack of control of the 'order' in which the areas of the ply are laid up. The need to carefully control the order of layup is emphasised by Elkington demonstrating how if a tow becomes stuck down in any two separate places at once there is potential for serious bridging between those two points, as shown schematically in image E of Figure 3 [43]. In order to correct this, some 'slippage' of the ply across the tool would be required, as shown graphically in Image F, but due to friction and the inherent tack of the material this slippage is often difficult or impossible. While a vacuum can apply consolidation in many different places at once, other systems use end effectors which only apply consolidation to a discrete area at any one time as shown in images A-C in Figure 3. When using these end effectors it is emphasised by numerous sources that it is important that the layup as a whole moves progressively as a 'front', working out from one area out over the rest of the ply to avoid creating bridges and voids [74][43][79].

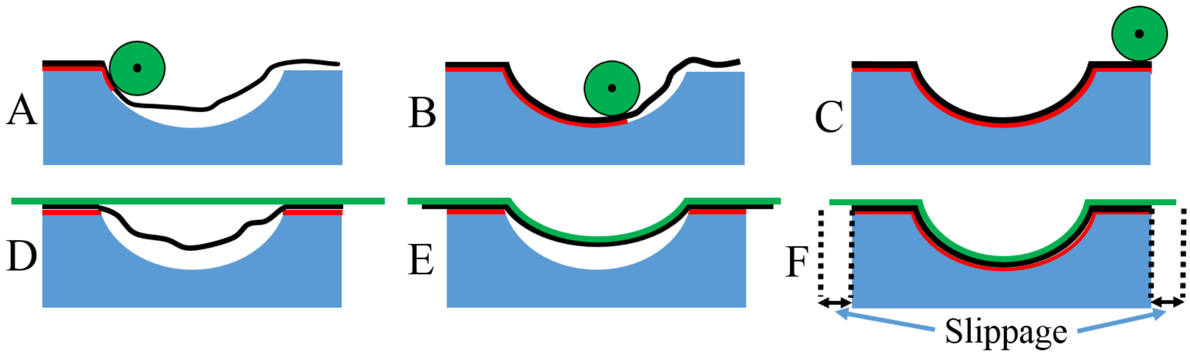

Figure 3: Timeline of 'progressive' consolidation (Top) and Vacuum consolidation (Below)

3.4.1. End effectors

In the automated environments many schemes have tried using a single roller to consolidate every shape, notably the vast majority of AFP and ATL machines [11] and the Lowflip concept [48]. It has been shown that cylindrical rollers will struggle to consolidate prepreg properly over complex surfaces, especially those with tight convex curvature. Flixeder states that the roller radii, even for very soft rollers must be less than that of the smallest radius on the tool [79]. Some projects have proposed complex end effectors using a combination of moving segments and compliant elements to combat this issue [80][81].

Instead of using more adaptable end effectors, some studies have used multiple end effectors each specialised to work in certain geometries [43][84]. Bjornsson successfully consolidated a single curvature component from cross plied UD prepreg. This was combined with a pick and place system and a backing film removal to form one of the most complete automated sheet layup systems. However the pick and place system did not move the ply onto the mould, this had to be done manually. A wide cylindrical roller was used to consolidate flat and convex surfaces while profiled non-cylindrical rollers were used for the internal corners. Elkington took a different approach, using 'presheared' plies of woven prepreg which had already been pressed into the shape of the mould to layup a sandwich panel type structure. Three compliant silicone end effectors were used; a cylinder for flat and convex surfaces, a profiled roller for single curvature concave surfaces and a silicone-metal hybrid wedge shaped probe for double curvature concave features. An example of a system which also focuses on controlling the layup order is patented by the Boeing Company, featuring a multitude of deformable elements which gradually form a stringer section starting across the top of the stringer and moving down the sides as the end effecter which specifically 'sweeps' gradually across the ply [82].

One of most novel end effectors is the A+ Glide system, which uses a very compliant inflatable roller to consolidate a top hat spar shape [76]. Very compliant elements were also proposed by Buckingham and Newell [46], where a large foam block was proposed to apply pressure to areas of the ply, a technique which was recently successfully used by Elkington in a forming study [70]. Compressed air has also been used as a consolidation tool, but rather than being inside an inflatable bladder, it was directly ejected onto the material to force it onto the mould, achieving as far as the author is aware the only example of 'non-contact' consolidation [83].

3.5. Other challenges

One of the surprising challenging aspects of automation is the removal of the backing attached to the ply, especially the initiation of the peeling [46]. Newell achieved this by removing the backing film straight off the roll and then reattaching is with a reduced adhesion prior to ply cutting. The ply was then held down on a vacuum table and the ply removed using a needle gripper. Bjornsson also used a vacuum table to secure the prepreg but used a second vacuum gripper rather than a needle to peel the backing off one of the backing layers off [84].

4. CONCLUSIONS:

With many competing designs providing limited information of their relative capabilities it is difficult to predict with any certainty which of these is the best suited to becoming a commercially viable process. Full stack forming for high quality components onto genuinely double curved moulds is unlikely to provide a satisfactory solution, and forming of individual or small numbers of plies is more likely to be the future. Many of the processes reviewed here have the potential to allow successful automated forming of a very specific set of shapes, but most of them are a long way off competing with hand layup in terms of versatility and capability. In the author's opinion it is unlikely that a single 'do-it-all' solution will emerge and there will be wide range of options. Consequently there will need to be a detailed understanding of the forming limits of each process and either the components geometry tailored specifically to the manufacturing process, or bespoke versions of the processes tailored to the specific parts.

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